

Transverse Momentum Distribution of J/ψ 's in Pb-Pb Collisions and Gluon Rescattering

Pengfei Zhuang^[1] and Jörg Hüfner^[2]

^[1] Physics Department, Tsinghua University, Beijing 100084, China

^[2] Institute for Theoretical Physics, University of Heidelberg, D-69120 Heidelberg, Germany

Abstract

The transverse momentum dependence of J/ψ suppression in relativistic heavy ion collisions is calculated from initial state gluon rescattering not only with nucleons but also with prompt gluons produced in nucleon-nucleon collisions in the early phase of the reaction. The second mechanism is new and turns out to be important in a description of the data for central collisions.

1 Introduction

Recently, the NA50 collaboration has presented the final analysis of transverse momentum distributions^[1] for charmonia produced in Pb-Pb collisions at 158 A GeV. For the J/Ψ , the values of $\langle p_t \rangle$, $\langle p_t^2 \rangle$ and $\langle M_t - M \rangle$ exhibit a similar trend as a function of the centrality of the collisions: they first increase and then flatten when the centrality increases, and finally turn steeply upward for the most central collisions.

It is commonly accepted^[2] that the new data on J/Ψ suppression in Pb-Pb collisions cannot be explained only by inelastic collisions of the J/Ψ with the nucleons of projectile and target. The anomalous suppression needs a new absorption mechanism, and the observed drop at large E_t ($\simeq 100$ GeV) is either considered as the expected onset of J/Ψ melting^[3, 4] in the picture of the quark-gluon plasma, or interpreted^[5, 6, 7] as an effect of the transverse energy fluctuations around its mean value determined by the collision geometry. The data on J/Ψ transverse momentum distributions

provide us additional interesting information and possibly a deeper insight into the underlying physics.

In a recent publication[8] we have drawn the attention to a close correlation of the values of $\langle p_t^2 \rangle(E_t)$ and the degree of anomalous suppression $\Delta S(E_t) = S_G(E_t) - S_{ob}(E_t)$, where $S_G(E_t)$ (G ="Glauber") is the suppression calculated from the inelastic scattering of the J/ψ on nucleons alone, while "ob" refers to the observed values. In the same paper we have proposed one explanation for this correlation: The escape of high p_t J/ψ from final state absorption in a QGP or an environment of comovers. Unfortunately, the theory required a new parameter. In the present paper we take an alternative point of view: We investigate whether the data on $\langle p_t^2 \rangle(E_t)$ can be described by an anomalous mechanism in the initial state. We have followed this line, since the bulk part of the observed $\langle p_t^2 \rangle$ seems to be generated in the initial state.

It is generally agreed that the additional transverse momentum broadening $\delta p_t^2 = \langle p_t^2 \rangle_{AB} - \langle p_t^2 \rangle_{NN}$ observed in nucleus-nucleus (AB) collisions over the one in nucleon-nucleon (NN) collisions arises in the initial state, i.e. before the production of the $c\bar{c}$ pair[12]. The two partons (mostly gluons) traverse nuclear matter thereby colliding with nucleons (thus acquiring additional p_t^2) before they fuse to the $c\bar{c}$. Indeed, the data for $\langle p_t^2 \rangle_{AB}$ show a linear relation with the path length of the gluons in the initial state as is well studied in pA and $S - U$ collisions[1]. In a nucleus-nucleus collision, especially with heavy nuclei, an additional phenomenon arises, the phenomenon of wounded nucleons. In the approach of prompt gluons proposed in refs.[9, 10] for the description of anomalous J/ψ suppression "wounded" nucleons are nucleons which contain additional prompt bremsstrahl gluons whose number is proportional to the number of inelastic NN collisions. In the approach of refs.[9, 10] the additional gluons lead to a larger inelastic cross section for a J/ψ on a wounded nucleon compared to a ground-state nucleon.

The wounded nucleon approach should also have an effect on the initial state. The gluons from projectile and target nuclei, which eventually fuse to form the $c\bar{c}$, encounter nucleons and wounded nucleons before they fuse. The interaction of these gluons with nucleons is identified as the main source

of the additional transverse momentum broadening δp_t^2 . If the encountered nucleon is wounded, δp_t^2 should be even larger. It is this effect, which we calculate in this paper.

In our calculation we rely heavily on the notation and on the parameters chosen in refs.[9, 10], yet our presentation is essentially self-contained. We first present the formulae for J/ψ suppression in Pb-Pb collisions calculated from inelastic J/ψ N interactions and from collisions with prompt gluons in the final state. Then we turn to the initial state and derive the formulae for the generation of the transverse momentum (Sect. 2). Then, in Sect. 3, we present the numerical results and compare with experiment, followed by the conclusions (Sect. 4).

2 Generation of additional transverse momentum via interaction with prompt gluons in the initial state

Fig. 1 is a schematic representation of J/ψ production in nucleus-nucleus collisions with particular emphasis to the prompt gluons in the initial and final state. The collision of a row of projectile nucleons on a row of target nucleons is depicted in a two-dimensional (time-longitudinal coordinate) plane and in the NN c.m.s. A gluon from a projectile nucleon and a gluon from a target nucleon fuse to produce a premeson at point O which has three dimensional space coordinates (\vec{s}, z_A) in the rest frame of the projectile A and $(\vec{b} - \vec{s}, z_B)$ in the rest frame of the target B, where \vec{b} is the impact parameter for the AB collision. The premeson propagates through the projectile and the target, and develops in time towards the asymptotically observed J/Ψ . During the propagation the premeson interacts with nucleons from the projectile and target. Since these nucleons have experienced collisions with other nucleons before their encounter with the $c\bar{c}$ premeson, and since they have radiated bremsstrahl “prompt” gluons (dashed lines), the $c\bar{c}$ premeson will also interact with these radiated gluons. Taking into account the two kinds of final state collisions of the premeson the J/Ψ suppression function

can be written as

$$S(E_t) = \int d^2\vec{b} d^2\vec{s} dz_A dz_B K(\vec{b}, \vec{s}, z_A, z_B, E_t) , \quad (1)$$

where E_t is the transverse energy which reflects the centrality of the collision, and the expression for the suppression kernel K is taken as[10]:

$$K(\vec{b}, \vec{s}, z_A, z_B, E_t) = \rho_A(\vec{s}, z_A) \rho_B(\vec{b} - \vec{s}, z_B) e^{-(I_A + I_B)} P(E_t | b) . \quad (2)$$

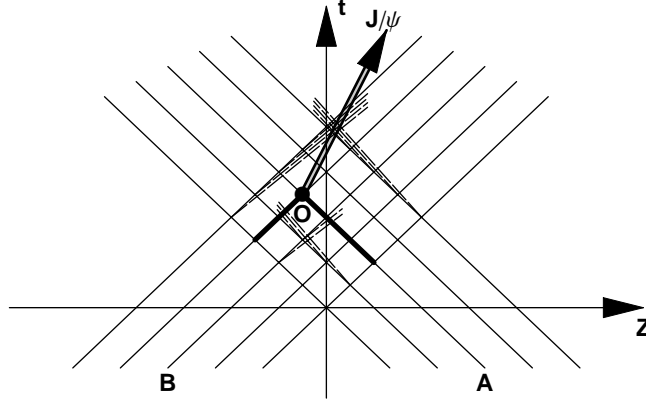


Figure 1: A two-dimensional (time-longitudinal coordinate) plot for J/Ψ production in a collision of nuclei A and B in the c.m.s. of the colliding nucleons. Nucleons are denoted by thin solid lines, the two gluons which fuse to form a premeson at point O are denoted by thick solid lines, while the bremsstrahlung gluons are drawn by dashed lines.

Here $\rho_{A,B}(\vec{r})$ is the density of the nuclei A and B, respectively. The final state J/Ψ absorption via the interaction with nucleons and prompt gluons in the geometric row labeled by the variables \vec{b}, \vec{s} is contained in the two exponentials given by

$$\begin{aligned} I_A(\vec{b}, \vec{s}, z_A, z_B) &= \int_{z_A}^{\infty} dz \sigma_{abs}^{\Psi N}(t_{\Psi}) \rho_A(\vec{s}, z) \\ &+ \sigma_{in}^{NN} \int_{z_A}^{\infty} dz \int_{-\infty}^{\infty} dz' \sigma_{abs}^{\Psi g}(t_{\Psi}) \Theta(t_g) \langle n_g \rangle(t_g) \rho_A(\vec{s}, z) \rho_B(\vec{s} - \vec{b}, z') , \\ I_B(\vec{b}, \vec{s}, z_A, z_B) &= \int_{-\infty}^{z_B} dz \sigma_{abs}^{\Psi N}(t_{\Psi}) \rho_B(\vec{s} - \vec{b}, z) \\ &+ \sigma_{in}^{NN} \int_{-\infty}^{z_B} dz \int_{-\infty}^{\infty} dz' \sigma_{abs}^{\Psi g}(t_{\Psi}) \Theta(t_g) \langle n_g \rangle(t_g) \rho_B(\vec{s} - \vec{b}, z) \rho_A(\vec{s}, z') \end{aligned}$$

where σ_{in}^{NN} is the inelastic NN cross section, $\langle n_g \rangle$ is the mean number of prompt gluons produced in a NN collision, and $\sigma_{abs}^{\psi N}$ and $\sigma_{abs}^{\Psi g}$ are the J/Ψ absorption cross sections for its interaction with a nucleon and with a prompt gluon, respectively. Effects of formation time for the development of a $c\bar{c}$ pair to the J/ψ and for the radiation of a gluon are taken care of by the time dependence of $\sigma_{abs}^{\Psi N}(t_\Psi)$ and $\langle n_g \rangle(t_g)$, respectively. Here t_Ψ is the time difference between the ΨN interaction point and the formation point O of the premeson, and t_g is the time difference between the Ψg interaction point and the NN interaction point which produces the prompt gluon. The Θ functions in I_A and I_B ensure that only the prompt gluons, which are created before the interaction with the effective J/Ψ , are taken into account.

Using the two-channel model for the evolution of a $c\bar{c}$ pair, the time dependent effective cross section $\sigma_{abs}^{\Psi N}$ can be expressed as[11]

$$\sigma_{abs}^{\Psi N}(\tau) = \sigma_{in}^{\Psi N} + (\sigma_{in}^{pre} - \sigma_{in}^{\Psi N}) \cos(\Delta M \tau) , \quad (4)$$

where σ_{in}^{pre} is the initial ($\tau \rightarrow 0$) and $\sigma_{in}^{\Psi N}$ the asymptotic ($\tau \rightarrow \infty$) absorption cross section, and ΔM is the mass difference between J/Ψ and Ψ' . We use values $\sigma_{in}^{\Psi N} = 6.7 \text{ mb}$ and $\sigma_{in}^{pre} = 3 \text{ mb}$ [10].

In the constituent quark model, the inelastic Ψg cross section differs from the inelastic ΨN cross section by a factor $3/4$ [9],

$$\sigma_{abs}^{\Psi g} = \frac{3}{4} \sigma_{abs}^{\Psi N} . \quad (5)$$

Within pQCD the time dependence of the mean number $\langle n_g \rangle$ of the radiated gluons can be calculated[9] with an adjustable parameter ω_{min} , the soft limit of the transverse momentum carried by the prompt gluons. In order to reduce the numerical efforts, it is parameterized[10] as a step function

$$\langle n_g \rangle(t_g) = \begin{cases} n_g^0 \frac{t_g}{t_0}, & t_g < t_0 \\ n_g^0, & t_g > t_0 . \end{cases} \quad (6)$$

In our numerical calculations we have used fixed values[10] $t_0 = 0.6 \text{ fm}/c$ and $n_g^0 = 0.75$ (corresponding to $\omega_{min} = 0.75 \text{ GeV}$) for Pb-Pb collisions at 158 A GeV.

To include the effect of transverse energy fluctuations which have been shown significant for the explanation of the sharp J/Ψ suppression in the domain of very large E_t values, we relate the mean number $\langle n_g \rangle$ to the transverse energy in the same way as the energy density[5] and the comover density[6],

$$\langle n_g \rangle \rightarrow \langle n_g \rangle \frac{E_t}{\langle E_t \rangle(b)} , \quad (7)$$

where the mean value $\langle E_t \rangle(b)$ is proportional to the number of participant nucleons at fixed b , $\langle E_t \rangle(b) = qN_p(b)$, and $N_p(b)$ is determined by the collision geometry. The function $P(E_t|b)$ in the suppression kernel (2) describes the distribution of transverse energy in events at a given impact parameter b . It is chosen as a Gaussian distribution[5]

$$P(E_t|b) = \frac{1}{\sqrt{2\pi q^2 a N_p(b)}} e^{-\frac{(E_t - \langle E_t \rangle(b))^2}{2q^2 a N_p(b)}} \quad (8)$$

with the parameters $q = 0.274 \text{ GeV}$ and $a = 1.27$ [5].

We now turn to calculate the J/Ψ transverse momentum within the mechanism of gluon rescattering in the initial state. Before the two gluons, one from the projectile and one from the target, fuse to form the $c\bar{c}$ premeson at point O , either of them may scatter off one or several nucleons and one or several prompt gluons, as shown in Fig.1. Via the exchange of transverse momentum at each interaction vertex, the mean squared transverse momentum of the J/Ψ is a function of the history of the two gluons,

$$\langle p_t^2 \rangle(\vec{b}, \vec{s}, z_A, z_B) = \langle p_t^2 \rangle_{NN} + \frac{\langle p_t^2 \rangle_{gN}}{\lambda_{gN}} \ell_{gN}(\vec{b}, \vec{s}, z_A, z_B) + \frac{\langle p_t^2 \rangle_{gg}}{\lambda_{NN} \lambda_{gg}} \ell_{gg}^2(\vec{b}, \vec{s}, z_A, z_B) . \quad (9)$$

Here the first term is the contribution from the $c\bar{c}$ production vertex in an isolated NN collision, while the second and third terms arise, respectively, from multiple gN and gg collisions before fusion. Since the number of the gN collisions is proportional to the number of nucleons which the two gluons encounter, the second term scales with the sum of the lengths of the two gluon paths,

$$\ell_{gN}(\vec{b}, \vec{s}, z_A, z_B) = \int_{-\infty}^{z_A} dz \rho_A(\vec{s}, z) / \rho_0 + \int_{z_B}^{\infty} dz \rho_B(\vec{s} - \vec{b}, z) / \rho_0 . \quad (10)$$

The constant before the length ℓ_{gN} in eq.(9) depends on the mean transverse momentum $\langle p_t^2 \rangle_{gN}$ acquired in a gN collision and on the mean free path λ_{gN} of a gluon in nuclear matter. The third term in eq.(9) is proportional to the number of NN collisions in which the prompt gluons are generated. Therefore, ℓ_{gg}^2 is a sum of two 2-dimensional integrations (similar to the second terms in I_A and I_B in the final state interaction),

$$\begin{aligned} \ell_{gg}^2(\vec{b}, \vec{s}, z_A, z_B) &= \int_{z_B}^{\infty} dz \int_{-\infty}^{z_A} dz' \langle n_g \rangle(t_g) \rho_A(\vec{s}, z) \rho_B(\vec{s} - \vec{b}, z') / \rho_0^2 \\ &+ \int_{-\infty}^{z_A} dz \int_{z_B}^{\infty} dz' \langle n_g \rangle(t_g) \rho_B(\vec{s} - \vec{b}, z) \rho_A(\vec{s}, z') / \rho_0^2 . \quad (11) \end{aligned}$$

The other factors in the last term of eq.(9) are: The mean free path $\lambda_{NN}^{-1} = \rho_0 \sigma_{NN}^{in}$ for inelastic NN scatterings (the source of the prompt gluons) and $\lambda_{gg}^{-1} = \rho_0 \sigma_{gg}$ the mean free path for the interaction of a gluon (which fuses to form the $c\bar{c}$) with a prompt gluon. We use $\sigma_{in}^{NN} = 32 \text{ mb}$ and $\rho_0 = 0.17/fm^3$, while $\langle p_t^2 \rangle_{gg}/\lambda_{gg}$ is considered as a free parameter. The effect of transverse energy fluctuations can also be included in the initial state interaction by making the transformation (7) for the mean number $\langle n_g \rangle$ of the prompt gluons, like in the final state interaction.

We will call ℓ_{gg}^2 the squared gluon length related to gg interactions. However, it is necessary to note that while ℓ_{gN} is a geometrical length, either term in ℓ_{gg}^2 is not a simply product of the two geometrical lengths, since production time effects of the prompt gluons are included via the mean number $\langle n_g \rangle$.

The expression (9) for the mean transverse momentum holds for a J/Ψ produced from the rows with coordinates \vec{b}, \vec{s}, z_A and z_B . In order to compare with the experimental data, we have to average. The average of a quantity $Q(\vec{b}, \vec{s}, z_A, z_B)$ at fixed transverse energy E_t is calculated from the suppression kernel K (eq.(2))

$$\langle Q \rangle(E_t) = \int d^2\vec{b} d^2\vec{s} dz_A dz_B Q(\vec{b}, \vec{s}, z_A, z_B) K(\vec{b}, \vec{s}, z_A, z_B, E_t) / S(E_t) . \quad (12)$$

Inserting expression eq.(9) into eq.(12) one obtains

$$\langle p_t^2 \rangle(E_t) = \langle p_t^2 \rangle_{NN} + \frac{\langle p_t^2 \rangle_{gN}}{\lambda_{gN}} \langle \ell_{gN} \rangle(E_t) + \frac{\langle p_t^2 \rangle_{gg}}{\lambda_{NN} \lambda_{gg}} \langle \ell_{gg}^2 \rangle(E_t)$$

$$= \langle p_t^2 \rangle_{NN} + \frac{\langle p_t^2 \rangle_{gN}}{\lambda_{gN}} \langle \ell_{gN}^{eff} \rangle(E_t) , \quad (13)$$

where we have introduced the effective gluon length $\langle \ell_{gN}^{eff} \rangle$ in nuclear matter defined by

$$\langle \ell_{gN}^{eff} \rangle(E_t) = \langle \ell_{gN} \rangle(E_t) + \frac{\langle p_t^2 \rangle_{gg}/(\lambda_{NN}\lambda_{gg})}{\langle p_t^2 \rangle_{gN}/\lambda_{gN}} \langle \ell_{gg}^2 \rangle(E_t) . \quad (14)$$

3 Results and discussions

To simplify the numerical calculations we use a constant nuclear density $\rho(r) = \rho_0 \Theta(R_A - r)$. Since the calculation of the average transverse momentum needs information of the suppression function $S(E_t)$, we first calculate the ratio of the J/Ψ to Drell-Yan cross sections $\sigma_\Psi(E_t)/\sigma_{DY}(E_t) = S_\Psi(E_t)/S_{DY}(E_t)$. Here S_Ψ is the J/Ψ suppression function eq.(1), and the Drell-Yan cross section S_{DY} is obtained by putting $I_A = I_B = 0$ in the kernel K of S . The results are shown in Fig.2 as a function of E_t together with the new data of the NA50 collaboration. The calculation is normalized at $E_t = 0$ (NN collision) to $\sigma_\Psi/\sigma_{DY} = 50$. In the absence of the Gaussian distribution in E_t (eq.(8)) and its fluctuations related to $\langle n_g \rangle$ (eq.(7)), we have the same results as in[10]. It is obvious that the final state interaction with only nucleons (dashed line) cannot reproduce the data. The results including final state interactions with prompt gluons (thin solid line) fit the E_t -dependence well, except for the fast drop at very large E_t values. According to refs.[5, 6, 12], the drop at high E_t arises from transverse energy fluctuations. Including the E_t fluctuations via eq.(7) the agreement with data is improved, but less than the data seem to require. The quality of the fit is about as good as in ref.[6] and the residual discrepancy in the agreement with data may have its origin in the E_t assignment (c.f. ref.[6]).

The average gluon lengths (eq.(14)) are plotted in Fig.3 as a function of E_t . The length $\langle \ell_{gN} \rangle$ in nuclear matter (dashed line) and the length $\sqrt{\langle \ell_{gg}^2 \rangle}$ related to prompt gluon contribution but without consideration of transverse energy fluctuations (thin solid line) have the same behavior and almost the same amplitude. They increase in the domain of small transverse

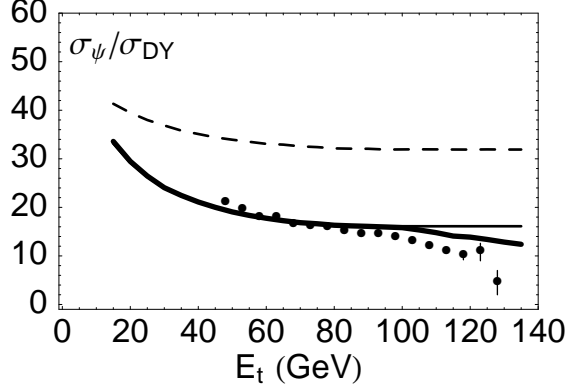


Figure 2: *The relative J/Ψ production cross section σ_Ψ/σ_{DY} in Pb-Pb collisions at 158 A GeV[13] as a function of transverse energy. The dashed line corresponds to the normal nuclear suppression, the thin solid line is obtained with final state rescattering with nucleons and prompt gluons, and the thick solid line is calculated including the fluctuations in transverse energy.*

energies ($E_t < 50$ GeV), and then saturate with E_t for values $E_t > 50$ GeV, where one observes large anomalous suppression and the prompt gluons become important. The saturation of the gluon lengths and of the transverse momentum (shown below) in this domain is due to the saturation of the amount of matter traversed by the initial gluons in the Pb-Pb collisions. As for the suppression in Fig.2, the contribution of the transverse energy fluctuations is significant only for very high transverse energies, $E_t > 100$ GeV (solid line in Fig. 3).

The effects of initial gN and gg scattering to the average transverse momentum are controlled by the two parameters, $\langle p_t^2 \rangle_{gN}/\lambda_{gN}$ and $\langle p_t^2 \rangle_{gg}/\lambda_{gg}$, respectively. The former may be extracted from experiments with light projectiles, and the latter is determined from the fit of eq.(9) to the data in the E_t region where prompt gluons become important. With the isolated NN contribution $\langle p_t^2 \rangle_{NN} = 1.11 (GeV/c)^2$ and the gN contribution $\langle p_t^2 \rangle_{gN}/\lambda_{gN} = 0.081 (GeV/c)^2/fm$ [1], the transverse momentum calculated with only gN scattering (dashed line in Fig.4), namely considering only the first two terms in eq.(9), agrees well with the data in the domain of $E_t < 50$ GeV, while it is clearly below the data outside this domain. Including the initial scattering with prompt gluons but without the factor eq.(7) (thin solid

line) and choosing the parameter $\langle p_t^2 \rangle_{gg}/\lambda_{gg} = 1/35 \langle p_t^2 \rangle_{gN}/\lambda_{gN}$, satisfactory agreement is obtained for all the data except for the last point, where the transverse energy fluctuations are expected to play a crucial rule. We include the fluctuations in E_t via the factor eq.(7) which becomes relevant only for ℓ_{gg}^2 in eq.(9) and arrive at the solid line in Fig. 4. There is some improvement, but the significance is difficult to judge, since there is only one data point with rather large error bar.

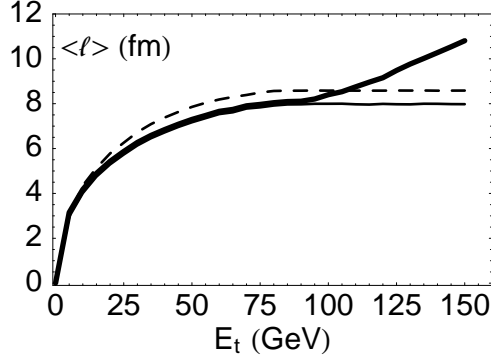


Figure 3: The gluon lengths $\langle \ell_{gN} \rangle$ (dashed line) and $\sqrt{\langle \ell_{gg}^2 \rangle}$ without (thin solid line) and with (thick solid line) fluctuations in transverse energy as a function of the transverse energy.

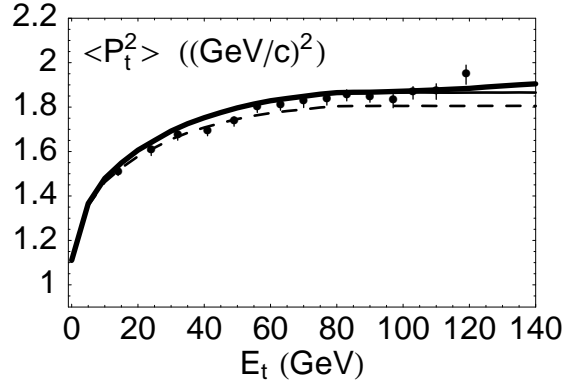


Figure 4: The average squared transverse momentum $\langle p_t^2 \rangle$ as a function of transverse energy. The data are from [1]. The dashed line corresponds to the normal gluon rescattering on nucleons, the thin solid line is obtained with gluon rescattering with nucleons and prompt gluons, and the thick solid line is calculated with also the fluctuations in transverse energy.

In order to see the results of our calculations in a different form, we display the experimental and calculated values for $\langle p_t^2 \rangle(E_t)$ as a function of $\langle \ell_{gN} \rangle(E_t)$, Fig. (5a), and as a function of $\langle \ell_{gN}^{eff} \rangle(E_t)$ (eq.(14)), Fig. (5b). While the dependence $\langle p_t^2 \rangle$ versus E_t is rather complicated with strong saturation effects for large values of E_t , the dependence $\langle p_t^2 \rangle$ versus $\langle \ell_{gN} \rangle$ or $\langle \ell_{gN}^{eff} \rangle$ is nearly a straight line. The dashed and solid lines in Figs. 5a,b correspond to the theoretical curves in Fig. 4. According to the definition eq.(13), the slopes of the two straight lines are the same and equal to $\langle p_t^2 \rangle / \lambda_{gN} = 0.081 (GeV/c)^2 / fm$.

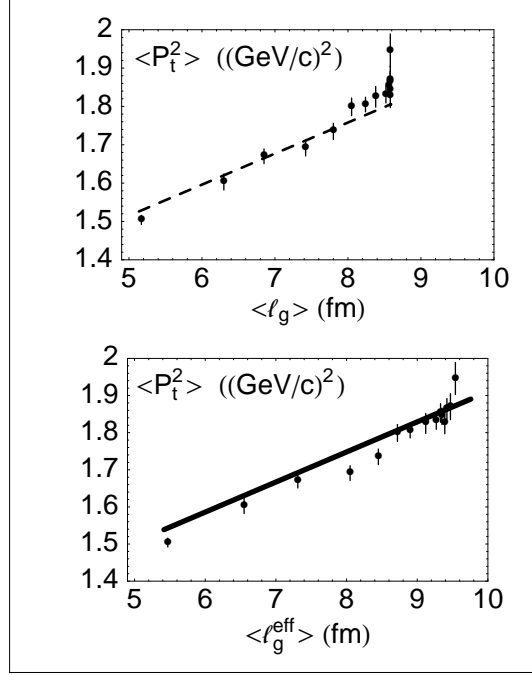


Figure 5: The observed $\langle p_t^2 \rangle(E_t)$ plotted versus the calculated $\langle \ell_{gN} \rangle$ and $\langle \ell_{gN}^{eff} \rangle$. The data are from [1].

Until now, we have studied the behaviour of $\langle p_t^2 \rangle$ as a function of E_t . In the experiment under consideration [1] the authors have also measured the p_t distributions within a given E_t interval. They have displayed their data as a ratio

$$R_{i/1}(p_t) = \frac{S(p_t|E_t^{(i)})}{S(p_t|E_t^{(1)})} \quad (15)$$

where $S(p_t|E_t^{(i)})$ is the differential distribution in p_t , normalized to $\int d^2 p_t S(p_t|E_t^{(i)}) =$

$S(E_t^{(i)})$. We have calculated $S(p_t|E_t^{(i)})$ by assuming a Gaussian p_t dependence. Then the suppression function $S(p_t|E_t^{(i)})$ can be written as

$$S(p_t|E_t^{(i)}) = \int d^2\vec{b} d^2\vec{s} dz_A dz_B K(\vec{b}, \vec{s}, z_A, z_B, E_t^{(i)}) \frac{1}{\langle p_t^2 \rangle(\vec{b}, \vec{s}, z_A, z_B)} e^{-\frac{p_t^2}{\langle p_t^2 \rangle(\vec{b}, \vec{s}, z_A, z_B)}}. \quad (16)$$

For the comparison with the experimental data, we divide the E_t region into five bins with mean values $E_t = 23, 48, 70, 90, 110$. The theoretical results together with the data are shown in Fig.6.

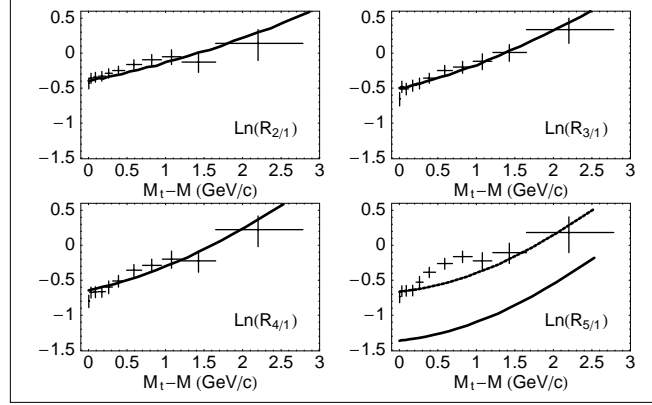


Figure 6: The ratio $R_{i/1}$ of the J/Ψ cross section with large value $E_t^{(i)}$ in the E_t bin i to the cross section with small $E_t^{(1)}$ in the first E_t bin as a function of $M_t - M$. We have plotted the logarithm of this quantity, since the global data seem to be exponentials $\exp(-(M_t - M)/T)$. There are five E_t bins corresponding to mean $E_t = 23, 48, 70, 90, 110$ GeV. The data are from [1]. The theoretical lines are calculated with initial and final state rescattering with nucleons and prompt gluons and with transverse energy fluctuations. For $R_{5/1}$, the solid line is our calculation, while the dotted line represents the calculated curve normalized to the data for small $M_t - M$.

For the figures we have not followed ref.[1], who plot $R_{i/1}$ versus p_t , but we rather plot $\ln R_{i/1}$ versus $\Delta M = \sqrt{M^2 + p_t^2} - M$. This representation leads to a straight line for the data integrated over E_t (cf.[1]). According to Figs. 6, this representation also leads to nearly straight lines. The solid lines represent our calculations. For all ratios, except $R_{5/1}$, the data are well accounted for. We see a problem in the quantity $R_{5/1}$. Our prediction

is consistently below the data, although our integrated value $S(E_t^{(5)})$ with $E_t^{(5)} = 110$ GeV lies above the data (Fig. 2). Thus we would have expected our calculation to be consistently above. In order to see whether calculated and experimental slopes agree we have normalized the calculated curve at small p_t to the data. The renormalized curve is shown by the dots and describes the data reasonably well, though there may be systematic deviations at large p_t . But since the error bars are too large, speculations about the discrepancies may be dangerous.

4 Conclusions

In this paper, we have studied the transverse momentum dependence of J/ψ production in Pb-Pb collisions at 158 AGeV. We have investigated whether the mechanism of prompt gluons can account for both effects, anomalous suppression of J/ψ and anomalous values of $\langle p_t^2 \rangle$. Here, “anomalous” is judged with respect to the “conventional” values of suppression and $\langle p_t^2 \rangle$ derived from the data of pA and $S - U$ collisions. The conventional physics is shown as dashed lines in Figs. 2 and 4, while the anomaly is the difference between the data and these lines. While the anomaly is large (an effect of a factor 2) in the suppression data, Fig. 2, the anomaly is small for the values of $\langle p_t^2 \rangle$. The difference between the data and the dashed line is of order 10%, if we use $\langle p_t^2 \rangle_{AB} - \langle p_t^2 \rangle_{NN}$ as the baseline. Within the model of prompt gluons we are able to describe the data for the J/ψ suppression (except possibly at very high values of E_t) by introducing one adjustable parameter

$$\frac{n_g^0 \cdot \sigma_{abs}^{J/\psi g}}{\sigma_{abs}^{J/\psi N}} = 0.56 \quad (17)$$

where n_g^0 is the number of produced hard prompt gluons per NN collision (eq.(6)) and the cross sections $\sigma_{abs}^{J/\psi g}$ and $\sigma_{abs}^{J/\psi N}$ describe the inelastic cross sections leading to the destruction of the J/ψ in collisions with a gluon and a nucleon, respectively. Within the same model we are also able to describe the data for $\langle p_t^2 \rangle$, Fig. 4, after a new parameter

$$\frac{\langle p_t^2 \rangle_{gg}}{\lambda_{gg}} \cdot \left(\frac{\langle p_t^2 \rangle_{gN}}{\lambda_{gN}} \right)^{-1} = 1/35 \quad (18)$$

is adjusted. The magnitude of the values eqs.(17) and (18) for the two parameters reflects the observation that the anomaly in the suppression is large (50%) while it is a small effect for the values of $\langle p_t^2 \rangle$.

We conclude: We have presented two possible explanations for the anomalous behaviour of the dependence of $\langle p_t^2 \rangle(E_t)$ in Pb-Pb collisions. In ref.[8] the effect is described as one of the final state while in this paper the gluon rescattering on bremsstrahl gluons in the initial state has been investigated as a possible source. In both approaches, satisfactory agreement with the data is achieved after adjusting one parameter in each calculation.

Acknowledgments: We thank Boris Kopeliovich who drew our attention to the initial state interactions. One of the authors (P.Z.) is grateful for the hospitality at the Institute for Theoretical Physics in Heidelberg, his work was supported by the grants 06HD954, NSFC19925519 and G2000077407.

References

- [1] M.C. Abreu et al. (NA50 Collaboration), Phys. Lett.**B499**(2001)85.
- [2] R. Vogt, Phys. Rept. **310**(1999)197;
C. Gerschel and J. Hüfner, Annu. Rev. Nucl. Part. Sci. **49**(1999)255.
- [3] J.P. Blaizot and J.Y. Ollitrault, Phys. Rev. Lett. **77**(1996)1703;
C.Y. Wong, Phys. Rev. **C55**(1997)2621;
D. Kharzeev et al., Z.Phys. **C74**(1997)307.
- [4] T. Matsui and H. Satz, Phys. Lett. **B178**(1986)416.
- [5] J.P. Blaizot, P.M. Dinh and J.Y. Ollitrault, Phys. Rev. Lett. **85**(2000)4010.
- [6] A. Capella, E.J. Feireiro and A.B. Kaidalov, Phys. Rev. Lett. **85**(2000)2080;
A. Capella. A.B. Kaidalov and D. Sousa, nucl-th/0105021.
- [7] J. Hüfner, B.Z. Kopeliovich and A. Polleri, nucl-th/0012003.

- [8] J. Hüfner and P. Zhuang, Phys. Lett. **B515**(2001)115.
- [9] J. Hüfner and B.Z. Kopeliovich, Phys. Lett. **B445**(1998)223.
- [10] J. Hüfner, Y.B. He and B.Z. Kopeliovich, Eur.Phys. J. **A7**(2000)239.
- [11] J. Hüfner and B.Z. Kopeliovich, Phys. Rev. Lett. **76**(1996)192.
- [12] S. Gavin and M. Gyulassy, Phys. Lett. **B 214**(1988)241;
J. Hüfner, Y. Kurihara and H.J. Pirner, Phys. Lett. **B215**(1988)218;
J. P. Blaizot and J. Y. Ollitrault, Phys. Lett. **B217**(1989)392.
- [13] M.C. Abreu et al. (NA50 Collaboration), Phys. Lett.**B449**(1999)128.

